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Steam Enhanced Remediation Research for DNAPL in Fractured Rock

Loring Air Force Base, Limestone, Maine

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Notice

The U.S. Environmental Protection Agency through its Office of Research and Development, Maine Department of Environmental Protection, United States Air Force, and SteamTech Environmental Services, Inc., funded, managed, and collaborated in the research described here. It has been subjected to the Agency's peer and administrative review and has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

All research projects making conclusions or recommendations based on environmental data and funded all or in part by the U.S. Environmental Protection Agency are required to participate in the Agency Quality Assurance Program. This project was conducted under an approved Quality Assurance Project Plan. Information on the plan and documentation of the quality assurance activities and results are available from the lead author.

Preface

The Maine Department of Environmental Protection (MEDEP) understands that cleanup of fractured bedrock aquifers is difficult, expensive, and in many cases technically impracticable, but we still find technical impracticability difficult to accept. Therefore, when reasonable arguments arose against a technical impracticability waiver for the Quarry, MEDEP was anxious to find a technology that would reduce the mass of contaminant trapped in the bedrock. MEDEP conceived the Quarry project as a modest effort, meant to try innovative methods of mass reduction on a limited budget over a limited time. The Quarry location seemed ideal for trying out new technologies – remote, in a harsh climate, and far from receptors. As it turned out, the modest effort was nurtured by the expertise and resources of many agencies and individuals. I am grateful for their efforts and grateful I got the chance to work with them.

MEDEP would like to acknowledge the following parties who were crucial to the completion of the project:

Funding was provided by U.S. EPA, through its Superfund Innovative Technology Evaluation (SITE) program. Ms. Annette Gatchett of EPA (SITE program) provided excellent management skills in providing funding and oversight of the steam injection program.

Special thanks to Dr. Eva Davis of U.S. EPA for assuming the role of technical lead for the entire steam injection project. Dr. Davis' invaluable contribution to the project was the key to our success. She maintained the project on track, resolved many of the technical problems and tracked all project data. Dr. Davis was a major contributor to this report.

Mr. Paul Depercin of U.S. EPA (SITE program) provided a great deal of support in the field as well as contract management.

Mike Nalipinski and Bill Brandon of EPA Region I have provided the team with outstanding support. Mr. Nalipinski invested more than seven years into the Loring remediation; his input in to the program helped resolve many obstacles we encountered. Mr. Brandon's technical expertise in the field of structural geology and his knowledge of the site geology helped the team in the decision making process.

Mr. David Strainge of the U.S. Air Force provided crucial funding and project oversight. Mr. Strainge has been an invaluable resource to the Air Force and the people of Maine in the ten plus years since the base went Base Realignment and Closure (BRAC).

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SteamTech Environmental Services, Inc., contributed funding and technical expertise. SteamTech contributed a great deal to the success of the research project. Hank Sowers, Dr. Gorm Heron, Dr. Steve Carroll, and Gregg Crisp were great instruments in the design and operation of the steam injection at the Quarry.

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Executive Summary

This report details a research project on Steam Enhanced Remediation (SER) for the recovery of volatile organic contaminants (VOCs) from fracture limestone that was carried out at an abandoned quarry at the former Loring Air Force Base (AFB) in Limestone, Maine. The project was carried out by United States Environmental Protection Agency (U.S. EPA) Office of Research and Development (ORD) National Risk Management Research Laboratory (NRMRL), U.S. EPA Region I, Maine Department of Environmental Protection (MEDEP), SteamTech Environmental Services, Inc., the United States Air Force (USAF), and experts from academia on characterization of fractured rock and steam injection remediation. U.S. EPA's Superfund Innovative Technology Evaluation (SITE) program participated in this research project to evaluate the SER technology in the fractured rock setting.

Loring AFB was added to the Superfund National Priorities List in 1990, and the Quarry was one of more than 50 sites on base that were addressed. The Quarry had historically been used for the disposal of wastes from construction, industrial, and maintenance activities at the base, and during remedial activities in the 1990s, approximately 450 drums were removed. Subsequent investigations showed that both chlorinated organics and fuel-related compounds were present in the ground water beneath the Quarry. Tetrachloroethylene (PCE) was detected at concentrations indicative of the presence of Dense Non-Aqueous Phase Liquids (DNAPL). The Record of Decision (ROD), signed in 1999, recognized that it was currently impractical to restore ground water in fractured rock to drinking water standards. However, an agreement was made between the USAF, MEDEP, and EPA Region I to use the Quarry to conduct a research project to further the development of remediation technologies in fractured rock, and with the hope of recovering contaminant mass to reduce the timeframe for natural attenuation of the remaining contaminants. In addition, the regulatory agencies hoped to develop guidance on characterization techniques for fractured rock. A Request for Proposals (RFP) for technologies to be tested at the site was issued in 2001, and SER was chosen from the proposals received.

With a technology and a vendor chosen, additional technology specific objectives for the research project were developed, which included determining if SER could: 1) heat the target area for remediation, 2) enhance contaminant recovery, and 3) reduce contaminant concentrations in the rock and ground water. Secondary objectives included determining if contaminants were mobilized outside of the treatment area, documenting the ability of SteamTech's effluent treatment systems to meet discharge requirements, determining operating parameters for fractured rock, and documenting costs.

Characterization activities were initiated in 2001 with the installation of process boreholes based on the agreed on treatment area and the preliminary design of the treatment system. These borings were cored and logged, and rock chip samples were collected from fracture surfaces for determination of contaminant concentrations. Additional characterization activities included discrete interval transmissivity testing and ground water sampling, conventional borehole geophysical and acoustic televiewer (ATV) logging, and interconnectivity testing. Based on the results of all the characterization activities and an updated conceptual site model (CSM), the steam injection and extraction system was revised to include steam injection at the eastern side of the target area, with extraction along the center line and the western side of the target area.

Construction of the system was initiated in August 2002, and the extraction system starting operation on August 30. Steam injection was initiated on September 1, and continued until November 19, when funding for the project ran out. Extraction was terminated on November 26. Throughout operations, EPA's SITE program collected effluent vapor and water samples to document the contaminant recovery rate and amount of contaminants recovered. SteamTech collected temperature data using 22 thermocouple strings, and documented changes in subsurface resistivity caused by temperature increases or by steam replacing water in the fractures using electrical resistance tomography (ERT).

Early in operations, it became apparent that steam injection rates were much lower than anticipated due to low transmissivities in the injection intervals and sparsely spaced fractures. In an attempt to inject more steam and increase the rate of heating, three extraction wells were converted to injection wells during operations. Although this significantly increased the amount of steam being injected, the amount of energy that could be injected during the limited-time project was still low, and the entire target zone for treatment could not be heated. The highest recorded temperature away from the injection wells was approximately 50°C, which was recorded approximately 4.5 meters (15 feet) from the nearest injection well. ERT was found to be capable of monitoring the heatup of the subsurface during SER; however, the magnitude of the resistivity changes determined was not consistent with the expected change based on prior laboratory measurements of resistivity of limestone as a function of temperature. Based on the limited duration of steam injection during this project, it cannot be determined conclusively that steam injection would be capable of heating the entire treatment area to the target temperature. However, since the rock chip sampling showed that most of the contaminants were located at the fracture surfaces or within 0.3 meter (1 foot) of the fracture surface, the heat that was injected was concentrated where the contaminants were found. It is possible that adequate treatment might have been achieved even without achieving target temperatures throughout the target zone.

Despite the limited heating that occurred, effluent vapor and water samples showed that after approximately three weeks of operations, the extraction rates started to increase, and they continued to increase for the duration of the project. The highest extraction rates were achieved at the end of the project, after steam injection had ceased and air injection was increased. This is believed to be due to air stripping of VOCs at the higher subsurface temperatures, which carried the vaporized contaminants to extraction wells. Effluent samples showed that more than 7.4 kg (16.2 lbs) of contaminants were recovered during the project, of which 5.0 kg (11.12 lbs) were chlorinated VOCs, 0.55 kg (1.22 lbs) were gasoline range organics (GRO), and 1.77 kg (3.9 lbs) were diesel range organics (DRO). Based on the high concentrations of PCE and DRO in some wells during the last round of sampling, it is believed that NAPL was about to be extracted.

Sampling of the effluent vapor and water streams just prior to discharge showed that the vapor and water treatment systems employed by SteamTech effectively treated these streams to meet discharge limitations. Ground water samples from two angled wells that extended below the treatment area showed that contaminants do not appear to have been moved downward by SER. Ground water samples from two wells just to the north and east of the treatment area showed that contaminants were not moved horizontally into those areas. Evaluation of operations data shows that higher steam injection pressure can be used in competent bedrock than are typically possible in unconsolidated media, and the importance of the co-injection of air and pressure cycling to enhance the transport of mobilized contaminants to extraction wells.

The evolution of the CSM as additional characterization information became available, and after the completion of the steam injection, allowed an evaluation of the importance of different characterization activities to understanding ground water and contaminant transport in fractured rock, and to the design and implementation of the SER system. It was determined that a variety of characterization activities are required to understand the flow system and contaminant distribution sufficiently for remediation system design and operation.

For large, simple-to-moderately complex fractured rock sites, SER may be an efficient and cost effective remediation technology for VOCs. However, for highly complex, low permeability fractured sites with low interconnectivity, such as the Loring Quarry, steam injection may not be the best method for remediation. In order for SER to be successful in such an environment, extensive characterization is needed, and extremely long injection times are likely necessary. Even with long injection times, heat losses may limit the ability to heat the entire target zone. For sites such as this, Thermal Conductive Heating (TCH) or Electrical Resistance Heating (ERH) may be more capable of uniformly heating the target zone, and may be effectively implemented with less characterization, resulting in an overall reduction in remediation costs. Further research is warranted on steam injection remediation in fractured rock in less complex sites, and on the application of ERH and TCH to contaminated fractured rock sites.

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Plates (Contained on Accompanying CD)

Acronyms and Abbreviations

AFB	Air Force Base
ALT	Advanced Logic Technologies
ARAR	Applicable or Relevant and Appropriate Standard
atm	atmosphere
ATV	Acoustic Televiewer
BCT	below casing top
BD	back drill
bgs	below ground surface
BIPS	Borehole Image Profiling System
BRAC	Base Realignment and Closure
BTEX	Benzene, toluene, ethyl benzene, and xylene
Btu	British thermal unit
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
COC	Contaminant of Concern
CSM	Conceptual Site Model
CVOC	Chlorinated Volatile Organic Compound
DCA	Dichloroethane
DCE	Dichloroethylene
DEP	Department of Environmental Protection
DNAPL	Dense Non-Aqueous Phase Liquid
DRO	Diesel Range Organics
EM	Electromagnetic
EPA	Environmental Protection Agency
ER	Electrical resistivity
ERH	Electrical Resistance Heating
ERT	Electrical Resistance Tomography
EX	Extraction
FID	Flame Ionization Detector
FS	Feasibility Study
ft	feet
GAC	Granular activated carbon

gpm	gallons per minute
GRO	Gasoline Range Organics
HLA	Harding Lawson Associates
HPFM	Heat pulse flow meter
I	Injection
kg	kilograms
kJ/hr	kiloJoules per hour
kPa	kiloPascals
kWh	kiloWatt hours
lbs	pounds
LNAPL	Light Non-Aqueous Phase Liquid
lpm	liters per minute
m	meters
MCL	Maximum Contamination Level
MEDEP	Maine Department of Environmental Protection
MERC	Methanol extracted rock chip
mg/kg	milligrams per kilogram
mg/l	milligrams per liter
MS/MSD	Matrix spike/matrix spike duplicate
msl	mean sea level
NAPL	Non-Aqueous Phase Liquid
NFCS	Nonfracture control sample
NRMRL	National Risk Management Research Laboratory
ORD	Office of Research and Development
OTV	Optical televiewer
PCE	Tetrachloroethylene
PID	Photo-Ionization Detector
ppmv	parts per million volume
QAPP	Quality Assurance Project Plan
QC	Quality Control
RFP	Request for Proposals
RI	Remedial Investigation
ROD	Record of Decision
RPD	Relative Percent Difference
SARA	Superfund Amendments and Reauthorization Act of 1986
scfm	standard cubic foot per minute
scmm	standard cubic meter per minute
SER	Steam Enhanced Remediation

SITE	Superfund Innovative Technology Evaluation
SOP	Standard Operating Procedure
TC	Thermocouple
TCE	Trichloroethylene
TCH	Thermal Conduction Heating
TDS	Total Dissolved Solids
TI	Technical Impracticability
TIO	Technology Innovation Office
USAF	United States Air Force
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
VEA	Vertical Electrode Array
VLF	Very low frequency
VOA	Volatile Organics Analysis
VOC	Volatile Organic Compound